

REQUIREMENTS FOR ROBOTS UTILIZED AT HAZMAT INCIDENT SITES

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Abstract

Robotic technology being developed for space applications such as the shuttle, space station, and planetary exploration has direct application here on earth as well. Robots enable people to remotely and therefore safely perform dangerous terrestrial operations such as bomb disposal, nuclear facility cleanup, and hazardous material handling. The Jet Propulsion Laboratory Emergency Response Robotics Project is developing a teleoperated mobile robot for use by the JPL Fire Department HAZMAT Team. The robot, called HAZBOT, enables remote reconnaissance of HAZMAT incident sites, areas where hazardous materials have been accidentally spilled or released, without risking team personnel. This paper will present the steps in manned HAZMAT response and the requirements for a robotic system to aid in performing these operations. The JPL HAZBOT mobile robot will then be discussed.

Introduction

A variety of robotic systems are currently being developed by NASA and other agencies to enable shuttle and space station crews to remotely perform tasks such as satellite servicing, space structure assembly, automatic exterior inspection, etc., eliminating the need for dangerous EVA missions. Robotic rovers for planetary exploration are also being pursued allowing exploration where it is simply not technically or economically feasible to send a manned mission. This technology has important terrestrial application as well by enabling remote operation in hazardous environments such as maintenance in nuclear facilities, weapons plant decommissioning, bomb and ordnance disposal, and hazardous material site cleanup, without risking human life.

This paper will discuss the operational requirements for robotic systems utilized in the remote reconnaissance of sites where hazardous materials have been accidentally released or spilled. In particular, this paper will focus on the area of emergency response missions where, due to proximity of people, extreme toxicity, or unknown nature, rapid mediation of the incident

is required. Robotic tools enable remote first entry and reconnaissance of a HAZMAT site rather than risking entry team personnel.

The next section describes the necessary steps in a HAZMAT mission; what actions must be performed to contain and mitigate the hazard. This is followed by a discussion of the operational requirements for robotic systems to aid in HAZMAT response. Finally the HAZBOT robot under development at JPL will be presented and its effectiveness at carrying out mission functions discussed.

Emergency HAZMAT Response

The JPL Fire Department HAZMAT Team provides immediate response to hazardous material incidents at JPL. In this type of laboratory environment HAZMAT missions can be broken into the following steps:

- Deployment - Movement and setup of personnel and equipment at incident site.
- Assessment - Assessment of incident based on available information and planning of entry/remediation.
- First entry - Reconnaissance of incident site to locate, characterize, and identify hazardous materials involved.
- Remediation - Containment and cleanup of hazardous materials.
- Close out - Decontamination of entry equipment and personnel as well as identification of incident cause and future prevention.



Figure 1 HAZMAT personnel in full protective clothing.

The most dangerous of these steps are first entry and remediation. First entry by HAZMAT personnel is particularly dangerous because the types of materials involved maybe unknown. Even with full protective suits and self contained breathing apparatus, as shown in Figure 1, entry team personnel are at great risk. Remediation requires personnel to be in continued contact with the hazardous materials increasing the risk of injury. These dangerous operations are an ideal application of robotics enabling remote reconnaissance and remediation of hazardous material spills without risk to personnel.

The special precautions that must be taken when sending personnel into an incident site, particular when the materials involved are unknown, places a variety of limitation on manned response. First the primary and backup entry teams must be identified, vital signs taken, and suited up. This process in itself can take over an hour delaying identification and remediation of the hazard. Self contained breathing apparatus

supply only 40 minutes of air. With safety margins and time required for decontamination this leaves only 20 minutes to enter and work within the site. Furthermore protective suits are very bulky restricting movement and vision limiting what work can be performed. Robotic systems that can be deployed in a matter of minutes and work within an incident site for hours are even more desirable considering these limitations on manned entry.

Robotic HAZMAT Response

In telcooperated robotic systems a human operator uses a local control station to command the robot at the remote site to perform specific mission functions. (This paper focuses on telcooperated systems and will not discuss autonomous or semi-autonomous operations.) In order for a robotic system to be effective in HAZMAT operations a variety of important issues must be addressed:

- Mobility - The robot must be able to move within the incident site and overcome obstacles.
- Size - The system must be able to gain entry and maneuver in the incident site.
- Manipulation - Interaction with the environment requires some type of robotic arm or manipulation capability.
- Sensing - In order to gather information about the environment as well as monitor itself the robot must have on-board sensing capability.
- Power - How the system is powered determines mission life.
- Protection - The system must be protected from damage by objects and materials at the incident site.
- Communication - Data and information must be transferred between robot and operator effectively.
- Operator Interface - Equally important is how information from the robot is presented to the operator and how the operator controls the robot.

Note that these eight areas are not independent from one another but are a convenient breakdown for the discussion here. The following sections elaborate on these issues including specific requirements for emergency

response missions based on input from the JF'L HAZMAT Team

Mobility

Mobility is the ability of the robot to move to and within the incident site. The type of locomotion used is of course dependent on the type of terrain that is expected to be encountered. A laboratory type setting like JPL requires the following mobility characteristics:

- Ability to climb up or down a 30cm ledge or over a 30cm berm.
- Traversal of exterior paved and grassy surfaces as well as smooth interior surfaces with grades up to 30 degrees.
- Climbing of exterior and interior stairs with grades up to 45 degrees.

Speed is not a critical factor since in most cases the distance between the deployment and incident site is less than 100m. Also, for safety purposes when operating in areas containing people, it may be desired to have maximum speed less than 4mph; walking speed. Slow speed also reduces the need for a suspension system to protect on-board equipment.

Size

The overall size of the robot is limited by the work environment and the tasks the system must perform. Size is closely related to mobility with the following specific requirements:

- Ability to turn around within a 1.2m wide hallway. (This is highly dependent on the mobility system employed.)
- Ability to fit through standard door frame (approximately 75cm wide and 2m tall).
- Ability to maneuver in tight and cluttered environments such as offices and labs with walkways only 1 m wide and multiple turns.

These requirements point to a robot roughly 60cm wide and 1 m long. The height of the system may be more dependent on mobility issues than the 2m door frame (i.e., climbing the +/-45 degree stairs require a very low center of gravity to ensure stability).

Manipulation

A robotic arm manipulator enables the system to perform important mission functions such as moving objects. The specific manipulation functions that need to be carried out during a HAZMAT incident site are:

- Use a key to unlock a door. This requires alignment, insertion, and rotation of up to 360 degrees of the key.
- Ability to turn and pull doorknobs and levers to open doors and cabinets.
- Ability to sample air (for chemical gas detection) around standard door frame from floor level to top of frame - 2m vertical reach
- Grasping and movement of chemical containers up to 4" in diameter and 10lbs in weight. Special orientation requirements and smooth motion may also be needed to ensure container contents are not disturbed or spilled.
- Ability to sample spill (approximately 50cc) for subsequent analysis outside of site.
- Ability to grasp and drag an injured person from the incident site.
- Ability to grasp and turn valves on piping and cylinders.

Note that not all these functions may be met by a single manipulation device. Specialized tools can be developed to enable a general robot arm to perform the specific functions listed above.

Speed and dexterity in performing the above activities are also important. In order to be a useful tool the robot must enable mission critical tasks to be performed in a reasonable amount of time. The manipulator should allow the operator to quickly *retrieve* and use tools to, for instance, unlock and open a door.

Sensing

Critical for HAZMAT missions is the ability to sense for airborne hazards such as combustible gases as well as specific chemical sensors to aid in material identification. The following chemical sensors were identified as important:

- General combustible gas - Critical to know if atmosphere contains a significant and combustible amount of flammable vapor.
- Oxygen - indicates ability of atmosphere to support combustion as well as danger to personnel without breathing apparatus.
- Carbon monoxide - A common toxic gas released during chemical reactions.

An aspirator pump and sensing hose should be used on conjunction with sensors so that the robot manipulator can maneuver the sensing hose to particular locations, such as a door frame, or particular objects.

A wide variety of other specific gas sensors may be desired depending on the material expected to be discovered at incident site. The robot should therefore be able to take additional sensors into the site as necessary for material identification. Other sensing, such as environment temperature, may also be useful. An IR (infrared) pyrometer enables non-contact temperature measurements of spills and containers to determine possible exothermic reactions.

Sensing of the robot system itself can provide important information to the operator. This may include:

- Power monitoring to indicate battery life remaining.
- Proximity and position sensing to avoid collisions as well as locate robot within environment.
- On-board temperature to protect from overheating electronics.
- Force/torque sensing on manipulator end-effector to enable compliant motion or force reflecting control.
- Force sensing on gripper to protect from damaging fragile objects such as glassware.
- Sensing of robot body roll & pitch to protect from roll-over.

Power

The primary requirement for a power system is supplying an adequate mission life. In the case of emergency response HAZMAT missions we have identified a target mission life of at least 2 hours. This provides the system enough time to gain access to the incident site and gather information on spill size and material involved.

Robot power can be handled in two ways, on-board power or power by way of a tether (or a combination of both). On-board power, whether battery or other source, will have a limited life. Batteries tend to be very heavy and will increase the power requirements to drive the vehicle particular up slopes. Long term operation can be achieved by the use of a tether however having a tether significantly affects mobility and range.

Protection

In the case of HAZMAT operation, protection refers to protecting the robot from harm by hazardous materials encountered at the incident site. The types of material used in exterior components of the robot therefore need careful consideration. Additional protection may be achieved by using a protective "suit" for the robot of the same material used in manned entry suit, viton/butyl for example.

An important consideration for HAZMAT response is operation in combustible environment; enclosed areas where a combustible concentration of flammable vapors may have accumulated. To be useful in such environments the robot must be specially designed so it does not provide a source of ignition. Enclosure of all sources of ignition in areas that can be purged of any combustible gases is recommended by the NEC (National Electric Code). Use of intrinsically safe components (those that do not use enough power to provide a source of ignition) and explosion proof components may also be desirable. Static discharge is also another source of ignition that must be addressed.

Finally, once the robot exits the incident site it must support decontamination. For the type of scenarios addressed here the robot should support decontamination by water wash down. This requires enclosing all water sensitive components, such as the computer, in water tight enclosures.

Communication

The communication issue is primarily one of medium, wire or wireless. Typical missions include operation of the robot within steel and concrete buildings that often causes problem with RF communication. Furthermore wide bandwidth RF video communication is expensive and requires significant power. The advantage of radio communication is freedom from a tether that may become tangled or snagged during a mission as well as enabling behind closed door operations such as riding an elevator.

Using a tether does have advantages such as reduced cost, signal reliability, ability to have hardwired kill button, and the ability to provide power to robot extending mission life. However tether management becomes a critical factor in mission operation ensuring it does not become snagged when going around corners, through doorways, or in the robot itself. The deployment method for tethers, from the control station or from the robot itself, is also important. Deploying the tether from the control station requires the robot to pullout and drag the entire tether as it moves increasing the chance of snagging. Tether deployment from the vehicle reduces the chance of snagging but adds size and weight to the robot itself. A fiber optical tether has the advantage of high bandwidth communication and a very small size. This makes it ideal for deployment from the robot and long distance mission of 1 km or more.

Operator Interface

In order to be an effective tool, the robot must be easily controlled by HAZMAT Team personnel. The Operator interface design is therefore critical to mission success.

We have looked primarily at teleoperation where the operator has complete control over all the robot functions. The operator therefore makes all the decisions based on feedback from the robot. The following are requirements for the operator interface:

- Visual feedback is critical both to enable inspection of the incident site (e.g., reading signs and labels) as well as movement of the robot and manipulator in the remote environment. Live video feedback is vital with multiple camera views and/or cameras that can be quickly repositioned to achieve the best

view. Also information overlaid on the video or a separate graphical display of sensor or system information is helpful. Because on-board video cameras provide limited viewing from the point of view of the robot, it may be desirable to have a computer display virtual model of the robot in its environment. This can provide the operator with a "remote reality": an overall picture of the robot within the remote real environment,

- Audible feedback is also desired and can provide important information such also locating leaks by sound and listening for calls of help from personnel within the site.
- Simple controls to activate robot function (e.g., driving, moving arm). Where possible operator controls should be in terms of mission functions.
- Automation of simple sub tasks such as tool retrieval and storage are also important. This enables the operator to focus on critical mission functions rather than having to control every action of the robot.

JPL Emergency Response Robotics Project

The primary goal of the Emergency Response Robotics project at JPL is to prototype a teleoperated mobile robot that can be quickly deployed by the HAZMAT Team enabling remote reconnaissance of an incident site without risk to team personnel^{5,7}. The preceding section provided a detailed breakdown of robot system requirements for emergency HAZMAT response.

A critical ingredient in the project is the direct involvement of the JPL Fire Department HAZMAT Team who helped establish the system requirements as well as operate and evaluate the robots under development. Other examples of the application of robotics to hazardous material operations are given in^{2,3,4}.

The Emergency Response Robotics Project began in October 1991 by acquiring two commercially available REMOTEC (Oak Ridge, TN) ANDROS Mark V-A mobile robots. (Commercial and off the shelf technology has been used wherever possible to reduce system cost and reinventing of the wheel. A reference book that covers many of the commercially available and research robots for hazardous operations is "A Compendium of Robotics Equipment Used in Hazardous Environments"¹.)

These systems served as a baseline for testing and training to determine required modifications for JPL HAZMAT operations.

The next section briefly describes the modifications to the ANDROS robot undertaken in the first year of the project leading to the HAZBOT II system. The section following this discusses the development of HAZBOT III, a major rebuild of the ANDROS system.

HAZBOT II

Training and experimentation with the JPL Fire Department HAZMAT Team was the most important factor in determining system requirements. The basic REMOTEC ANDROS Mark V system addressed many of the requirements of the previous section:

- Tracked drive with articulated front and rear sections enabling stair and obstacle climbing.
- 5-DOF manipulator with parallel jaw gripper.
- 100m tether for communication (video, audio, and data).
- On-board battery power with optional trickle charge over tether.
- Sized to fit through standard door way (28" wide, 42" long and 36" height in stowed configuration)

A variety of quick "experimental" modifications were made to the system to explore possible improvements including:

- New operator control panel replacing on/off toggle switches for arm joint control with potentiometers in a user-friendly layout.
- Development of specialized key tools for unlocking doors.
- Mounting of the pan/tilt camera on movable boom allowing better viewing angles during manipulation tasks.
- Addition of a laser depth cueing system to aid in manipulation tasks.
- Addition of a winch system to aid in door opening.

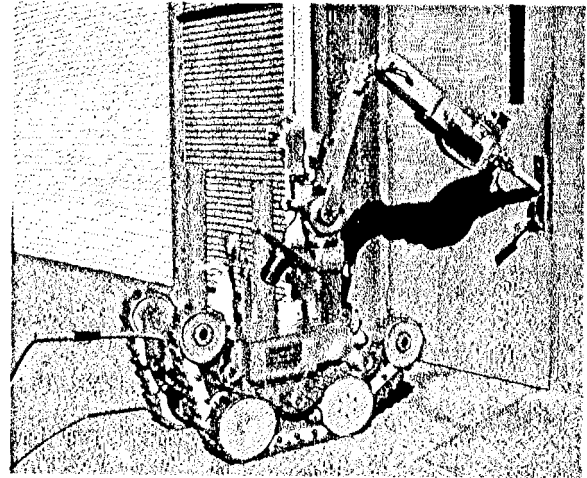


Figure 2 HAZBOT II opening door during demonstration mission

At the end of the first year of the project, a simulated HAZMAT reconnaissance mission was carried out by the JPL HAZMAT team using the modified robot called HAZBOT II. The mission included: opening the outside door of incident site building that had a thumb latch style handle as shown in Figure 2; navigating to the chemical storeroom where a spill was suspected; unlocking and opening the storeroom door; and operation in the very small storeroom locating a simulated chemical spill ⁶.

Although the use of mobile robots in HAZMAT operations was shown feasible" by this first year demonstration, a variety of issues were identified that must be addressed for the system to be used in real response missions:

- Redesign of the robot so that it can operate in an environment that may contain combustible gases with little risk of igniting those gases. This is particularly important in first entry situations where the type of hazard is unknown and potentially combustible.
- Redesign of the robot with a smooth profile and appropriate scaling so that it can be easily decontaminated after a mission.
- Improvement of speed and dexterity of manipulator,
- Continued enhancement of the operator controls.

- Addition of tetherless operation to allow deployment of vehicle greater than 100m from incident site.

The next section describes how these requirements and the lessons learned in the first year of the project have been used to develop the HAZBOT III system.

HAZBOT III

A major redesign of the REMOTEC system was undertaken to address the system requirements enumerated in the previous section. The key driver in design of the new system was the need for operation in potentially combustible atmospheres. A two tiered approach was used to address this design requirement. First, all electrical components that may cause electrical arcs or sparks during normal operation were replaced with solid state devices. This included using solid state relays instead of mechanical relays and replacing the brushed DC motors with brushless motors. Second, all areas of the robot that contain electrical components that could fail and provide a source of ignition are positively pressurized so any combustible vapors from the environment can not enter the system. Other key changes include:

- New 6-DOF manipulator (enclosing all motors and electronics with channels for pressurization) with significant increases in speed and stiffness. Also smooth profile to ease decontamination and reduce the possibility of snagging during manipulation tasks. (Manipulator has 40-lb payload capacity at its 5 ft reach and a 40-lb maximum grip force.)
- Provisions for two movable booms on torso that also includes channels for pressurization. (One currently being used for a pan/tilt camera.)
- Specific gas (OX and CO) and general combustible gas sensors integrated into forearm which draws samples in through tip of gripper. Sensor data displayed at operator control station.
- New on-board computer with 10 axis close-loop control of manipulator and camera systems as well as data acquisition system. (REMOTEC system used open-loop control.)
- On-board sensors for monitoring pressurization, battery power, and internal temperature.

- New Operator control station with two 13" video monitors (for two on-board color cameras) and a 486 PC with 16" graphical display of system and sensor data as Shown in Figure 3.

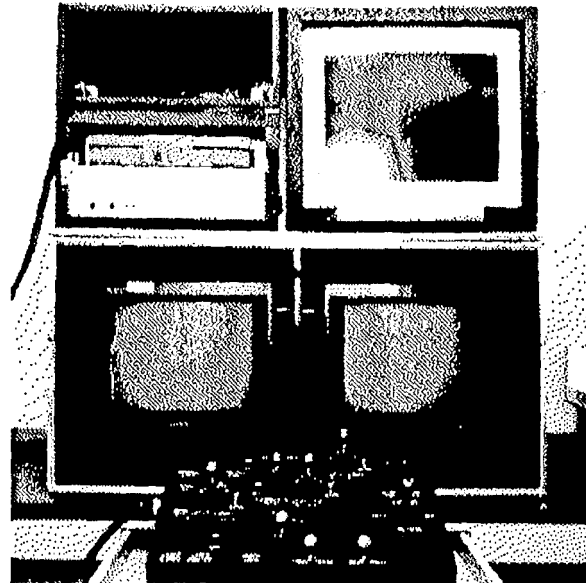


Figure 3 HAZBOT III operator control station

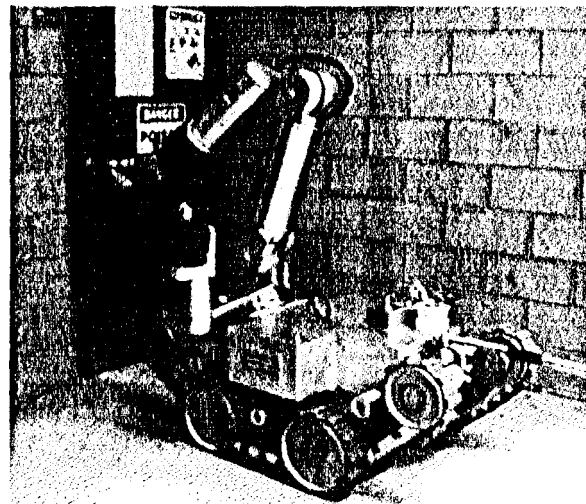


Figure 4 HAZBOT III mobile robot

Thus far HAZBOT III has been used by the JPL HAZMAT Team in three demonstration response missions. In the first demonstration HAZBOT III was used to locate the reason for a simulated alarm in the hazardous material storage

facility at JPL. This required the robot to unlock and open an exterior gate, unlock and open an internal door (as shown in Figure 4), locate material leaking from cabinet, and open cabinet and identify cause of spill - a ruptured container of waste material.

The second simulated response mission was to a laboratory containing a fume hood. The robot was used to open a door and gain entry to the building, unlock and open the door to the laboratory, locate and visually inspect fume hood identifying hazard, open fume hood and right container of simulated combustible material.

These first two missions were primarily to prove the functionality of the system and include training at the demonstration site before the mission. The most recent mission required members of the HAZMAT Team to respond to a simulated incident without prior knowledge of incident type or location. In fact the operator of the robot had never been inside the building where the incident was staged. **The system was** used to gain access to the site through a locked gate and locate the suspected hazard within the building in less than an hour. Upon exiting the site HAZBOT III was successfully decontaminated by water wash down as shown in Figure 5. This mission demonstrated the readiness of the **system for actual field operations.**

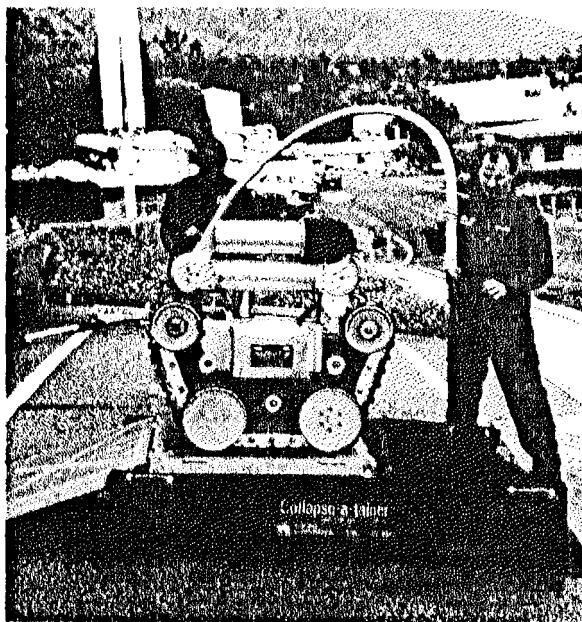


Figure 5 Decontamination of HAZBOT III

A variety of enhancements are currently underway. A simple side-view animated graphic of HAZBOT is being added to the computer display. This will allow the operator to quickly identify the configuration of the manipulator rather than having to scan the robot with the pan/tilt camera. Other sensors are being added to monitor the roll and pitch of the vehicle chassis and the position of the articulated tracks and feed this information back to the operator as well. (Note that is important to avoid information overload on the operator. The computer monitors the sensor data and provides warning to the operator when there is potential danger.)

A radio link for tetherless operation is planned for the future. We have done initial testing to determine effective frequencies for transmitting through buildings given size and power constraints. We are also planned to add stereo viewing capability to overcome depth perception problems during manipulation tasks,

Lessons Learned

We believe that mobile robots can be effective tools for reconnaissance of HAZMAT incident site. Perhaps more important, robots remove people from particularly dangerous operations such as first entry thereby protecting human life. A variety of important lessons have been learned in developing the HAZBOT robots for HAZMAT response:

Robot speed - The major task for the robot system is entry into the incident site: unlocking and opening of doors; climbing stairs and obstacles; and negotiating tight surroundings. It is therefore vital to develop tools and strategies to effectively carryout these tasks. In particular the manipulation system should enable the operator to quickly retrieve and use tools to, for instance, unlock a door. Slow actuation can also lead to boredom of the operator increasing the chance of mistakes. The camera system should also provide quick viewing of the robot and environment to prevent collisions, etc. One of the big advantages of using robots is the quick deployment while the HAZMAT entry team is setting up. The robot must therefore be able to gain access to a site in less than an hour so that it can collect information before the entry team is ready to go in. An additional option is to look at combined entry where entry personnel unlock and open doors but the robot enters rooms first

as well as provides video/audio monitoring of entry team personnel,

Robot size - The size of the HAZBOT system is larger than necessary for its primary mission - first entry and reconnaissance. The 28" wide robot requires careful alignment to pass through doors and negotiate laboratory areas. The strength of the arm is not needed for most mission functions. A smaller more maneuverable system that can still open doors may be better suited for reconnaissance tasks.

Operator interface - A good operator interface is critical if teleoperation is to be effective. Members of the HAZMAT Team do not necessarily have strong technical background or extensive time for training. The interface must therefore be intuitive, provide the operator with the information they need, and where possible prevent the operator from making mistakes.

Depth perception - Manipulation tasks are very difficult with monocular viewing with single video camera. Addition of simple depth cueing devices or a stereo camera system is therefore very desirable.

Customer Involvement - The direct involvement of the JPL Fire Department HAZMAT Team and JPL Safety personnel has been key in the development of a system that they can use for actual HAZMAT response.

Summary and Conclusion

Robot technology being developed for space applications have an important terrestrial roll as well. This paper has identified many of the requirements to effectively utilize robots in HAZMAT incidents. This includes:

- Ability to maneuver at incident site, traversing hallways, going thorough doorways, and negotiating stairs and obstacles.
- Ability to gather information at site through on-board video cameras and chemical sensors.
- Ability to manipulate objects at the incident site; opening cabinets, righting tipped over container, deploying absorbent pads, etc.

- Ability to safely enter areas containing combustible gases as well as support decontamination after a mission.

The JPL HAZBOT III robot addresses many of the preceding requirements and demonstrates the effectiveness of using robots in HAZMAT response. We believe that robot technology is currently ready to be utilized in HAZMAT and other dangerous operations. In fact not taking advantage of robot technology continues to put human life in danger on a daily basis.

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